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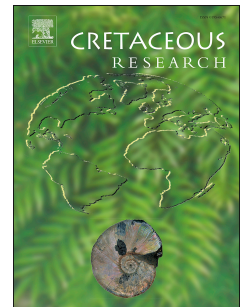
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Dinocyst stratigraphy and palaeoenvironmental interpretation of the Cretaceous/Paleogene boundary at Stevns Klint, Denmark

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ABSTRACT

A re-examination of the uppermost Maastrichtian chalks and an expanded section of the Fish Clay (Fiskeler Member) undertaken at Stevns Klint, Denmark, one of the classic outcrops of the Cretaceous/Palaeogene boundary, has identified diverse and abundant dinoflagellate cyst assemblages, which are compared with earlier dinoflagellate cyst (dinocyst) studies. The uppermost part of the white coccolith chalk (Sigerslev Member) of the uppermost Maastrichtian is placed in the *Palynodinium grallator* Zone. The overlying 'Grey Chalk' (Højerup Member) represents a shallower-water marine succession that is characterised by a series of dune-like structures. The last common occurrence of *P. grallator* is within the Højerup Member, confirming the Danian age for the Fish Clay (Fiskeler Member) and a latest Maastrichtian age for the *P. grallator* Zone. Within the Fiskeler Member, *Damassadinium californicum* (previously known as *Danea californica*), a key biostratigraphical marker, is only intermittently present, while the distributions of *Senoniasphaera inornata* and

Xenocodinium reticulatum provide useful biostratigraphic control. The well-preserved dinocysts of the Fiskeler Member are replaced by reduced assemblages in the Cerithium Limestone Member with only pollen grains recorded.

Keywords: K/Pg boundary, dinoflagellate cysts, biostratigraphy, Fiskeler Member

1. Introduction

In an investigation of the Stevns Klint, Maastrichtian–Paleogene succession, Hart et al. (2005) identify an expanded section of the boundary clay at Kulstirenden. As earlier studies of the dinocyst assemblages had been undertaken on much thinner successions of the boundary clay, this research aims to record the dinocyst changes in more detail across the K/Pg boundary.

While the basal Paleocene ‘Global Stratigraphic Section and Point’ (GSSP) is located in Tunisia (Molina et al., 2006), the Cretaceous/Paleogene (K/Pg) boundary at Stevns Klint, Denmark, remains an important reference point (Damholt and Surlyk, 2012). Stevns Klint includes the original site where the K/Pg boundary was first described by Desor (1847), lying between the coccolith chinks of the Maastrichtian and the bryozoan-rich chinks of the lower Danian. Desor (1847) also included the Faxe (Fakse) Quarry in his original definition of the Danian. While this working quarry is located only 17 km to the west of Rødvig, and has exceptionally interesting occurrences of bryozoan mounds and cool-water corals (Bernecker and Weidlich, 1990, 2005; Willumsen, 1995; Surlyk and Håkansson, 1999), other invertebrate fossils (Graversen, 2001), gastroliths (Noe-Nygaard, 1975) and evidence of coprolites (Milàn, 2010), the K/Pg boundary was not exposed there during our fieldwork. The old quarries at Holtug and Boesdal contain similar features and were also un-sampled.

The K/Pg transition is exposed almost continuously along the ~14 km-long cliff from Rødvig in the south to Bøgeskov in the north (Fig. 1). As reported by Hart et al. (2004, 2005), the Fish Clay, now renamed the Fiskeler Member by Surlyk et al. (2006), has been found to display considerable variation along the length of the cliffs at the eastern end of the Stevns Peninsula. At Kulstirenden the Fiskeler Member attains its maximum thickness (~50 cm). It is worth noting that in the definition of the GSSP the greater thickness of the boundary clay at El Kef, as compared to Stevns Klint, was used (Molina et al., 2006, p. 265) as evidence of the greater continuity of sedimentation in the Tunisian section. While this is certainly true at Rødvig and Højerup, the Kulstirenden exposure is quite comparable in thickness to that at El Kef. In their definition of the basal-Paleogene GSSP at El Kef, Molina et al. (2006, p. 265) recorded that there was no 'mass extinction' of dinocysts across the boundary and *Damassadinium californicum* – while at the base of the boundary clay in Scandinavia – appears 10 cm above the base of the boundary clay in the El Kef succession (Brinkhuis and Leereveld, 1988; Brinkhuis and Zachariasse, 1988; Donze and Méon, 1997). Despite the relatively low numbers of *D. californicum* three of the voting members of the Paleocene Working Group supported the FO of *D. californicum* as marking the boundary while 11 voted for the base of the boundary clay and, therefore, the impact event as the marker for the GSSP.

In recent years there have been a number of papers on the Stevns Klint K/Pg boundary succession, including a revision of the lithostratigraphy (Surlyk et al., 2006). The micropalaeontology and stable isotope stratigraphy have been described, in some detail, by Schmitz et al. (1992), Hart et al. (2004, 2005) and Rasmussen et al. (2005). Missing from all these recent investigations is any re-assessment of the

organic-walled dinocyst stratigraphy which has, in the past, been somewhat problematic.

There have been a number of dinocyst investigations at Stevns Klint, dating back to the 1960s. These include the works of Morgenroth (1968), Wilson (1974), J.M. Hansen (1977) and H.J. Hansen et al. (1986). Unfortunately, these investigations all used samples collected from the thinner sections of the Fiskeler Member. Hultberg (1985, 1986, 1987) did sample from slightly thicker parts of the Fiskeler Member, but the representativeness of some of his results has been questioned (Brinkhuis et al., 1998). In particular, two of Hultberg's (1986) Fiskeler Member samples contained a monospecific or near-monospecific assemblage of *Manumiella druggii*, which Hultberg interpreted as indicative of a lagoonal or brackish-water environment. J.M. Hansen (1977), H.J. Hansen et al. (1986) and Brinkhuis et al. (1998) all found more diverse assemblages at these locations. Furthermore, despite sampling from the slightly thicker parts of the Fiskeler Member, Hultberg only had eight samples within that member that actually contained dinocysts. Isotopic data from Stevns Klint presented by Hart et al. (2005) indicate potential environmental changes on a scale that Hultberg's sampling resolution would not be expected to achieve.

The primary objectives of our research are, therefore: 1) to increase the sampling resolution through the Fiskeler Member, which will provide a more detailed analysis of the dinocyst assemblages and species distributions across the K/Pg boundary at Stevns Klint; and 2) to use this new information on dinocyst stratigraphy to make comparisons with the distribution of these taxa from a number of other K/Pg boundary sites.

2. Geological setting

Forming the edge of the Stevns Peninsula in eastern Sjaelland, Stevns Klint is located ~40 km south of Copenhagen (Fig. 1). The cliff, which varies in height between 20 and 41 m, hosts several quarries along its 14 km length (Surlyk, 1979; Hart et al., 2004, 2005; Surlyk et al., 2006; Damholt and Surlyk, 2012). One of the first descriptions of Stevns Klint and the classic Cretaceous–Paleogene boundary sections, dates back to the eighteenth century (Abildgaard, 1759), but it was not until a century later that the complicated stratigraphy of the boundary was appreciated. Desor (1847) was the first to recognise the K/Pg boundary, while Rosenkrantz (1924) later described the palaeontology of the Maastrichtian and Danian strata. Together with Faxe (Fakse) Quarry, Stevns Klint constitutes the classic type area of the Danian Stage in Europe (Surlyk, 1979), but has been passed over as the Global Stratotype Section and Point for the base of the Danian because of its rather complex stratigraphy and lack of many key species of planktic foraminifera (Hart et al., 2004, 2005). The two localities used in this investigation are at Højerup, where most previous field studies have taken place (Schmitz et al., 1992; Hart et al., 2004, 2005) and Kulstirenden, which is located approximately 8 km to the north of Højerup.

Although laterally variable over the ~14-km long cliff, the composite stratigraphical sequence at Stevns Klint can be divided into five major lithological units (Hart et al., 2005; see Fig. 2 here) all of which have now been re-named by Surlyk et al. (2006). Except where stated otherwise, the following lithological details are derived from Hart et al. (2004, 2005) and Surlyk et al. (2006).

Low, rounded chalk mounds constitute the lowermost 5–10 m of the visible white coccolith chalk which is now known as the Sigerslev Member of the Tor Formation. The mounds grade upwards into ~20 m of *Zoophycos*-rich, horizontally-bedded

chalks, which host gently undulating lines of (generally) small black flints. Two features are present near the top of this member. There is a prominent, laterally-continuous nodular flint layer approximately 3–4 m below the Fiskeler Member (Fig. 3) at Højerup. At Harvig there are two phosphatised ‘hardgrounds’, approximately 100 mm apart, that are located ~ 30 cm above this flint horizon. Along the section northwards, towards Højerup, these merge into a single horizon. This line of flints (and the overlying hardground) can be followed along almost all of Stevns Klint and appear to be a reliable datum level (Surlyk et al. 2006, plates 7,10). At Rødvig this line of flints is just below beach level and rarely visible. On the coast to the south-east of Kulstirenden it is visible in the cliff just below the Fiskeler Member as the overlying Højerup Member is locally absent.

The Højerup Member is <4 m thick at Højerup and consists of grey-coloured, bryozoan- and *Thalassinoides*-rich chalk that was deposited in low, elongate, asymmetric mounds (3.5 to 4 m in height and with a basal dimension of ~25 m). Flint bands populate parts of the more gently-dipping northern slopes (~5° compared to ~15° for the southern slopes). At Kulstirenden, the Højerup Member is very thin or completely absent where the Fiskeler Member is at its thickest (Hart et al., 2005, fig. 7). At this location, the hardground at the boundary between the Sigerslev and Højerup members is immediately below the Fiskeler Member, almost giving the impression of a phosphatised sub-K/Pg boundary hiatus.

The Fiskeler Member lies within the troughs formed by the mounds in the underlying chalk. At some locations along Stevns Klint it can be missing as a result of the erosion at the top of the Cerithium Limestone Member. At Højerup, the maximum thickness of the clay is 7 cm (Christensen et al., 1973). At Kulstirenden the clay attains a maximum thickness of 45–50 cm in the centre of a large trough but

thins away from this centre so that at some locations it is absent from the succession (Hart et al., 2005). Where the clay is thickest, at Kulstirenden, the Højerup Member is absent and the clay lies just above the hardground that marks the boundary between the Sigerslev and Højerup members.

Christensen et al. (1973) divided the Fiskeler Member into four units: 1) the lowermost grey, laminated marl; 2) black marl, with pyrite concretions, that is often stained reddish-yellow in weathered outcrops; 3) black, laminated marl; 4) light grey marl also containing pyrite concretions. Figure 4 shows the Fiskeler Member at Kulstirenden where most of the samples for this study were collected.

The Fiskeler Member is observed to grade into the overlying Cerithium Limestone Member, with small lenses of chalk near the transition (making the boundary imprecise). Schmitz et al. (1992) reported the presence of a hiatus marked by an erosion surface but this has not been confirmed, especially in the expanded succession at Kulstirenden. The Cerithium Limestone Member is formed of <1 m of yellowish-white hard chalk with two hardgrounds at its uppermost boundary at Kulstirenden, which converge into a single hardground at other locations, including Højerup and Rødvig. This surface is regionally important as a sequence boundary (Rasmussen et al., 2005; Hart et al., 2011) and can be seen cross-cutting parts of the succession along the length of Stevns Klint. The overlying, bryozoan-rich chinks (Korsnæb Member) are cream-coloured, bryozoan-rich packstones and wackestones that occur as large asymmetric mounds. These mounds are on a much larger scale than those recorded from the Højerup Member and are best seen east of Rødvig, in the old quarries of Boesdal and immediately north of the old church at Højerup (where they were previously quarried).

3. Material and methods

Over the last few years several suites of samples have been collected from various locations along Stevns Klint by Malcolm Hart, Sean Feist, Eckhart Håkansson and Claus Heinberg. Of these, thirty-one were selected for palynological processing and analysis, with two slides prepared for each sample. For each slide 300 dinocyst specimens were counted; bisaccate pollen, spores and foraminiferal test linings were noted but did not form part of this count. The Gonyaulacoid/Peridinioid (G/P) and Protoperidinioid /Gonyaulacoid (P/G) ratios were calculated.

The G/P ratio calculated here follows Harland (1973), whereby $G/P = nG/nP$; n =number of species (identified as G/P^{species}). The G/P ratio was also calculated using $G/P = nG/nP$; n =number of specimens (identified as G/P^{specimens}) in order to allow comparison with some other authors. The P/G ratio follows Versteegh (1994), whereby $P/G = nP/(nP+nG)$; n = number of specimens.

Twenty-seven of the thirty-one samples selected for our investigation were collected from Kulstirenden. The K8 samples came from the white coccolith chalk of the Sigerslev Member immediately below the prominent flint horizon, only two of which were sent for processing (K8/7 and K8/5). The KUL/I and KUL/K samples were collected between the prominent flint horizon and the hardground(s) that usually mark the boundary between the Sigerslev and Højerup members. To complete the Maastrichtian succession, four samples (L5 series) were selected from the Højerup Member at Højerup, because this member is missing in the accessible section at Kulstirenden. Sixteen, mostly contiguous samples (KU14–29), represent the Fiskeler Member at Kulstirenden. Samples KU45–50 (excluding KU48, which was not sent for processing) were collected from the Cerithium Limestone Member. By using this selection of samples there has been a complete coverage of the K/Pg

transition (Fig. 5). The sampling of the Fiskeler Member is particularly detailed and this has allowed a more complete analysis of the dinocyst stratigraphy than has previously been the case.

4. Palynological processing

The full processing procedure is, perhaps unusually, described here as it was the sample preparation methods adopted by Hultberg (1985, 1986, 1987) that concerned Brinkhuis et al. (1998). All samples were processed in the Palynology Laboratory of the Natural History Museum (London) in February 2005 by Jonah Chitolie. Samples were processed using standard (see Batten, 1999) palynological techniques (hydrochloric acid followed by hydrofluoric acid for demineralisation). Oxidation was not deemed necessary, however, because of the well-preserved nature of the palynomorphs.

The chalk samples all weighed between 119 and 166 g, while the clay samples weighed 9–13 g. All the samples were cleaned of surface contamination either by scraping the outer layer of the sediment with a stainless steel scalpel (for hard chinks), or by brushing with a dry nylon toothbrush (for clays, marls and soft chinks). The clean samples were oven-dried at 100°C for approximately ten hours. After drying and weighing (chalk samples weighed 50–118 g; clay samples weighed 5–8 g), the samples were placed in glass beakers: 2-litre beakers for the chalk and 1 litre for the clay. 100 ml of distilled water was added to each sample, subsequently followed by a small amount of 50% hydrochloric acid, with any reaction being allowed to subside before the addition of more acid. The chalk samples foamed due to their high reactivity.

After being washed through a 15 μ m sieve with filtered tap water, the residues were returned to the glass beakers where concentrated hydrochloric acid was added to eliminate un-dissolved carbonates. After further washing, the samples were placed in 250 ml polypropylene beakers where 50% hydrofluoric acid was added and left overnight. Samples were then washed through a 15 μ m polyester sieve.

The recovered residues, in almost all of the samples, contained well-preserved palynomorphs, some of which were transparent. All residues were examined before mounting and any that were found to contain calcium fluoride precipitate were treated with 50% hydrochloric acid and heated at 80°C for approximately one hour. The residues were divided in two, with one part stained using Bismark brown R.

For each sample two glass coverslips were cleaned and placed on a warm plate. A small amount of residue was placed in a vial and mixed with polyvinyl acetate. The residue was pipetted onto the coverslip and left to dry. A small amount of Elvacite was used as the mounting medium and was placed on each slide and then inverted onto the coverslip. Elvacite is made by dissolving 20 g of Elvacite 2044 resin (a trade name for methacrylate resin) in 35 ml of xylene. The slides were kept in a fume hood over night and then placed in a drying oven at 80°C for two hours.

5. Dinocyst distribution

A range of well-known taxa have been identified in this study, all of which are listed and counts given in Appendix 1, while the ranges of selected taxa are shown in Table 1 and images of selected taxa are shown in Figure 6. Taxonomic classification follows Fensome et al. (2008), although, it is accepted that some aspects of the taxonomy may be in need of further investigation and revision.

5.1. Kulstirenden – Sigerslev Member (K8 samples)

Sample K8/7 was dominated by *P. grallator*, which recorded ~30% (112 specimens) of the count. The *Achomosphaera-Spiniferites* complex of dinocysts, together accounted for 80 specimens or ~ 25%, with *A. ramulifera*, *S. ramosus multibrevis* and *S. ramosus reticulatus* being particularly common. The *Achomosphaera-Spiniferites* complex of dinocysts is here defined as a grouping of all species and subspecies belonging to these two genera. *Palaeoperidinium pyrophorum* showed its highest abundance at this level with 15 specimens counted. This produces a G/P^{species} ratio of 25; G/P^{specimens} ratio of 293 and a P/G ratio of 0.05 (see Fig. 7).

Sample K8/5 was similar to K8/7 with *P. grallator* comprising 180 specimens or 30% of the cysts counted, and the *Achomosphaera-Spiniferites* complex of dinocysts accounting for 79 specimens, c. 25% of the count, *S. ramosus multibrevis*, however, was not quite as abundant as in K8/5, while *P. pyrophorum* was only observed once. Species diversity was 25 and 21 for K8/7 and K8/5, respectively, similar to the L5 series of samples from Højerup. This produces the following ratios: G/P^{species} = 21; G/P^{specimens} = 305 and P/G = 0.

5.2. Kulstirenden – Højerup Member (KUL samples)

KUL/K produced a near-monospecific assemblage of *P. grallator* (235 specimens; 87.7%). Of the other taxa only *Oligosphaeridium complex* and *S. ramosus gracilis*, were found in abundances greater than one. *Impagidinium cristatum* was relatively common (32 specimens). There were no peridiniacean cysts resulting in a G/P^{species} ratio of 0. Only 17 species and sub-species were observed in this sample, the lowest

diversity of dinocysts encountered (see Fig.7). KUL/I was barren and did not contain any dinocysts.

5.3. Højerup – Højerup Member (L5 samples)

These four samples showed a dinocyst assemblage almost completely dominated by gonyaulacacean cysts. Species diversity varied between 27–30 (Fig. 7). The only peridiniacean cyst observed in these samples was *Palaeoperidinium pyrophorum*, which was found in samples L5/60-65 and L5/290-295, but was absent from the other two. Where it did occur, abundance was low: 3 specimens in the former sample and 8 specimens in the latter. Consequently, the G/P^{species} ratio increases and decreases from 26 to 0 and from 29 to 0 from the lowest to uppermost samples (see Fig. 7). Similarly the $G/P^{\text{specimens}}$ ratio varied between 0–103. The P/G ratio varied from 0.01 to 0 and 0.03 to 0 from the lowest to the uppermost samples (see Fig. 7). Collectively, the *Achomosphaera*-*Spiniferites* complex cysts are the most abundant species (78–143 specimens) in the Højerup Member samples, comprising between 24.6–45 % of the count. Within this complex, *A. ramulifera*, *A. sagena*, and several subspecies of *Spiniferites ramosus* were identified (see Fig. 6).

Tanyosphaeridium xanthiopyxides is a common species throughout all of the samples (14–37 specimens). *Impagidinium cristatum*, is also common; its abundance is consistently higher in the older samples (16/12 specimens in L5/60-65 and L5/125-130 respectively). Of the other taxa, only *P. grallator*, *Spiniferites ramosus ramosus*, *Spiniferites ramosus gracilis* and *Hystriosphæridium tubiferum* appear in any significant numbers. In addition, abundant algae and foraminiferal linings were noted in all of the samples, particularly L5/125–130.

5.4. Kulstirenden – Fiskeler Member (KU samples)

Of the species that were recorded below the boundary, *I. cristatum* was absent and *P. grallator* disappears above KU15. The *Achomosphaera*–*Spiniferites* complex cysts were still present in large numbers (between 60–114 specimens in samples KU14–22). *Tanyosphaeridium xanthiopyxides* continued its predominance from the L5 samples (20–81 specimens) forming between 5 and 26% of the total species count. Species that were not present below the K/Pg boundary but were present in samples KU14–KU29 include *Fibrocysta capitata*, *Senoniasphaera inornata* as well as *Cribroperidinium* spp. and *Thalassiphora pelagica*. These species were present in low numbers (1–8 specimens) and not seen in every KU sample. A cribroperidinioid cyst attributed here to *Cribroperidinium* sp. A of Brinkhuis and Schiøler (1996), has been recorded by Brinkhuis et al. (1998), Slimani et al. (2010) and Vellekoop et al. (2014). *Cribroperidinium* sp. A of Brinkhuis and Schiøler (1996) is considered a transitional form with *Carpatella cornuta* sensu stricto (Damassa, 1988). It has a short apical horn and spongy appearance but lacks the definite antapical protrusion of *C. cornuta* s.s. This taxon only occurs at Stevns Klint above the K/Pg boundary in the Fiskeler Member. This is consistent with other studies (Brinkhuis et al., 1998; Schiøler et al., 1997; Vellekoop et al., 2014) which have described transitional forms such as this occurring in the lowermost Danian, below the first appearance of *C. cornuta* s.s., however, Vellekoop et al. (2015) and Slimani et al. (2010) record its first appearance just below the boundary. The acritarch *Raphidodinium* sp. cf. *armatum* was always present in these samples and occurred in significant numbers (23–59 specimens) from samples KU19 to KU23 and KU27–29. *Xenicodinium reticulatum* was observed in low numbers (2–5 specimens) in two of the uppermost

samples (KU23 and KU29). In addition, *Damassadinium californicum* was only observed intermittently and as single to rare occurrences.

Peridinioid cysts were found to be more common and diverse than below the boundary, increasing in number up through the succession. There were more peridiniacean specimens recorded in the higher, more productive KU samples (KU24-29). *Palaeoperidinium pyrophorum* continued to be intermittently present and *Cerodinium diebelii* was often common (8–47 specimens) with rare *Deflandrea* spp. and *Palaeocystodinium australinum*. *Manumiella seelandica* (formerly, *M. druggii*) was only observed intermittently and in variable numbers (1–14 specimens). *Trithyrodinium evittii* was very common, becoming abundant (163 and 214 specimens) in the highest samples (KU28 and KU29, respectively), where it accounted for 50–65% of the assemblages. Species diversity (31–41) remained high in the KU samples, similar to the L5 and K8 samples throughout the clay, with an overall increase through the upper samples (see Fig. 7).

No dinocysts were observed in samples KU48–KU50 (Cerithium Limestone Member), although bisaccate pollen grains were recorded.

6. Biostratigraphy

Wilson (1974), using a relatively limited number of samples, was the first to propose a dinocyst zonation for Denmark. Subsequently, J.M. Hansen and co-workers (J.M. Hansen, 1977, 1979, Kjellström and Hansen, 1981) and Hultberg (1986), working across a range of sites in southern Scandinavia (including Stevns Klint), generated a zonation for the uppermost Maastrichtian and lowermost Danian. More recently, Schiøler and Wilson (1993) refined Wilson's (1974) dinocyst zonation for the whole of the Maastrichtian. The problem with many of these zonations is a lack of precise

information on how the sampling of the variable lithostratigraphical units was accomplished, especially in Denmark.

In the discussion of the K/Pg boundary at El Kef (Molina et al., 2006) the stratigraphical value of *Danea californica* (= *Damassadinium californicum*) was regarded as important: it was one of the potential criteria for the definition of the GSSP.

Sample KUL/I contained no dinocysts but was collected immediately below the hardground surface at the top of the Sigerslev Member. This suggests that hardground formation (which also characterises the upper levels of the Cerithium Limestone Formation) inhibits the preservation of dinocysts. This has previously been noted by FitzPatrick (1992) in the Turonian chalk succession of the United Kingdom.

Palynodinium grillator occurs, often in large numbers (e.g., 110–235 specimens) in the upper parts of the Sigerslev Member, aside from sample KUL/I adjacent to the hardground and continues in reduced numbers (0–38) throughout the Højerup Member to the very top of the Maastrichtian. In the Højerup Member, *P. grillator* occurs in reduced numbers while *Achomosphaera ramulifera* and *Impagidinium cristatum* are present in reasonable numbers (6–20 and 2–16, respectively) before the latter species disappears at the K/Pg boundary. Records of rare *P. grillator* (1–5 specimens) within the Fiskeler Member are possibly the result of inclusion of minute clasts of chalk within the samples processed. Vellekoop et al. (2015) record the first appearance of *P. grillator* above the K/Pg boundary in Tunisia and Slimani et al. (2010) describe a similar occurrence from Morocco. This occurrence of *P. grillator* was, in both cases, interpreted as the southward migration of a cooler water species in response to cooling during the early Danian.

Palynodinium minus occurs throughout the Fiskeler Member, from KU15–KU28, but in low numbers (1–5 specimens). This species has reduced lateroventral protrusions similar to that described as *P. cf. grallator* by Machalski et al. (2016) which was noted from the Maastrichtian of Lechówka, south east Poland. The sporadic occurrence of *P. grallator* and *P. minus* above the K/Pg boundary is, therefore, not unusual.

Damassadinium californicum does occur in the Stevns Klint material (see Table 1), but is very rare. It is present only in the Fiskeler Member, although the environmental changes recorded higher in the succession probably were a limiting control on its reported range.

The occurrence of *Cribroperidinium* sp. A of Brinkhuis and Schiøler (1996), although rare within the Fiskeler Member is quite characteristic, appearing in the sample below *D. californicum* which is only millimetres above the K/Pg boundary as defined by Molina et al. (2006). A number of other taxa (e.g., *Fibrocysta capitata*, *Cribroperidinium* spp.) also occur throughout the Fiskeler Member, which contains a diverse dinocyst assemblage throughout (31–41 species per sample). This result is different to the near-monospecific association described by Hultberg (1985, 1986, 1987).

Appearing in KU23 is *Xenicodinium reticulatum*, another marker species to have a first appearance within the Fiskeler Member, including *Trithyrodinium evitii*, *Senoniasphaera inornata* and *Manumiella seelandica*. We suggest, therefore, that the upper *X. reticulatum* Sub-zone of the *D. californicum* Zone, of the lowermost Danian can be recognised here.

6.1 Comparison with biostratigraphic zonations of Scandinavia

In the following paragraphs the results from this study are discussed in relation to previously published distributions of stratigraphically significant dinocysts from southern Scandanavia.

6.1.1 *Palynodinium grallator* Zone (new definition)

The uppermost part of the upper Maastrichtian is characterised by the *P. grallator* Zone (Wilson, 1974; Schiøler and Wilson, 1993). This zone, is here defined by the first and last common occurrences of *P. grallator*, (K8/7–KUL-K) respectively and is different to Wilson's (1974) Zone Vb, as the top of this zone was defined by the last occurrence of *P. grallator*. The uppermost part of this zone has been divided into the *Tanyosphaeridium magdali* (= *T. xanthiopyxides*) and *Thalassiphora pelagica* Subzones by Schiøler and Wilson (1993). In previous studies at Stevns Klint, and throughout the Danish region (e.g., Hultberg, 1986; Schiøler and Wilson, 1993), *T. xanthiopyxides* has always been referred to as *T. magdali*. Lentin & Williams (1993), however, noted that *T. magdali* was almost certainly a junior synonym of *T. xanthiopyxides*.

Kjellström and Hansen (1981) also included the *Chiropteridium inornatum*–*Palynodinium grallator* Concurrent Range Zone in their zonation, with its upper boundary corresponding to the Maastrichtian–Danian (K/Pg boundary). This Concurrent Range Zone was later renamed the *Senoniasphaera inornata*–*Palynodinium grallator* Concurrent Range Zone by Hultberg (1985). The common occurrence of *T. xanthiopyxides*, and the consistent occurrence of *Thalassiphora pelagica*, in this study, through the Højerup Member and into the Fiskeler Member, prevents the recognition of these subzones as defined by Hansen (1977) and Kjellström and Hansen (1981).

6.1.2 *Damassadinium californicum* (*Danea californica*) Zone

Originally named after its taxonomic junior synonym *Danea mutabilis* (Hansen, 1977) this zone begins with the first occurrence of *D. californicum* (Kjellström and Hansen, 1981; Hultberg, 1985). The zone extends over much of the lower Danian and has previously been divided into two subzones (*Chiropteridium inornatum* and *Hafniasphaera cyrptovesiculata* Subzones), of which only the lower one (the *Senoniasphaera inornata* Subzone, formerly the *Chiropteridium inornatum* Subzone) has been observed at Stevns Klint (e.g., J.M. Hansen, 1977). Hultberg (1985, 1986) did not record *D. californicum* at Stevns Klint but this is unsurprising as it is relatively rare in our samples (1–3 specimens in some, but not all samples of the Fiskeler Member). The rare but consistent occurrence of *S.inornata* here, with its first appearance just below that of *D. californicum*, within the Fiskeler Member, supports this zonation. The *Senoniasphaera inornata* Subzone was divided into three zonules: *Carpatella cornuta*, *Xenicodinium rugulatum*, *Xenicodinium reticulatum* Zonules, by Hansen (1977) and Kjellström and Hansen (1981), but Hultberg (1986) added a fourth: the *Fibrocyta axialis* Zonule. These zonules, as defined by Hansen (1977) and Kjellström and Hansen (1981), were not all recognised here in the samples from Stevns Klint.

6.1.3 *Carpatella cornuta* Sub-zone (new definition)

This subzone should contain *C. cornuta* (Kjellström and Hansen, 1981), however, it is not recognised here. The transitional form, *Cribrorperidium* sp. A of Brinkhuis and Schiøler (1996) present here, is known to occur in lowermost Danian samples (Brinkhuis et al. 1998; Slimani et al., 2010; Schiøler et al., 1997; Vellekoop et al.,

2015). *Xenicodinium reticulatum* is not present. Kjellström and Hansen (1981) indicated that *Cordosphaeridium inodes longipes* was not found at this level and this is consistent with our results. *Cribroperidinium* sp. A of Brinkhuis and Schiøler (1996) is, therefore, interpreted as a marker species for the basal Danian from samples KU14–KU20.

6.1.4 *Xenicodinium reticulatum* Sub-zone

This subzone is only tentatively identified here within the Fiskeler Member as samples from all over southern Scandinavia (as attempted by Kjellström and Hansen, 1981) have not been investigated. *Xenicodinium reticulatum* was observed in samples KU23–KU29 and so is the basis for the identification of this subzone. No dinocysts were observed in samples KU45–KU50, although bisaccate pollen grains were recorded.

7. Discussion

7.1 *K/Pg boundary sections*

K/Pg boundary sections world-wide, fall into three categories; those proximal to the Chixculub impact site (e.g., Texas, Alabama, Georgia, Gulf of Mexico), distal sites (e.g., Denmark, Tunisia, Italy, Austria, etc.) and those that are intermediate in character e.g. Demerara Rise (MacLeod et al., 2007) and New Jersey (Olsson et al., 1997).

Stevns Klint is an important distal K/Pg boundary site, with others located in Southern Spain, Morocco, Tunisia, Egypt, Italy, Austria, Czech Republic, Poland, etc. These sites extend across a wide range of latitudes from 'Tethyan' to 'Boreal' locations and dinocyst studies from these areas have produced varying results in

terms of species diversity and abundance (Molina et al., 2006; Donze and Méon, 1997; Brinkhuis and Leereveld, 1988; Brinkhuis and Zachariasse, 1988; Brinkhuis et al., 1998; M'Hamdi et al. 2015; Vellekoop et al., 2015).

Our information on the dinocyst stratigraphy of Stevns Klint can be compared to many of these areas with some reliability, including successions from a wide range of different environments and water depths.

7.2 *Dinocyst occurrences and biostratigraphic markers*

In addition to the publications already mentioned, there is extensive literature on K/Pg boundary successions that include dinocyst studies. Many of these studies describe diverse and abundant dinocyst assemblages, characteristic of the uppermost Maastrichtian and lowermost Danian (Wilson, 1974; J.M. Hansen, 1979; De Coninck and Smit, 1982; Firth, 1987, 1993; Hultberg and Malmgren, 1987; Habib et al., 1992; Moshkovitz and Habib, 1993; Schiøler and Wilson, 1993; Olsson et al., 1997; Schiøler et al., 1997; Nøhr-Hansen and Dam, 1997; Mohamed and Wagreich, 2013; Vellekoop et al., 2016). Others, often the thinner successions, are usually not very productive and yield poor or barren dinocyst assemblages (Gedl, 2004; Mohamed et al., 2013; Beiranvand et al., 2014; Machalski et al., 2016).

Conclusions relevant to this study that can be made from the literature:

1. *P. grallator* often, and quite widely, typifies the uppermost Maastrichtian (Wilson, 1974; Schiøler and Wilson, 1993) with *C. cornuta*, *D. californicum* and *S. inornata* frequently characterising the lowermost Danian, (Kjellström and Hansen, 1981) though the exact details of their ranges are dependent on the individual site, the sampling interval used and issues relating to re-working of fine sediment across the boundary.

2. An increase in the abundance of peridinioid species, demonstrated by the G/P and P/G ratios across the K/Pg boundary into the lower Danian, has been recognised previously (Brinkhuis et al., 1998; Prauss, 2009). More specifically, an increase in the abundance of *Trithyrodinium evittii* is noted by Brinkhuis et al. (1998) and Slimani et al. (2010). The predominance of *T. evittii* has also been recognised in central and northern Europe (Schiøler et al., 1997) and the north-eastern USA (Firth, 1987, 1993).
3. Vellekoop et al. (2015) describes the K/Pg boundary succession at Elles (75 km south of El Kef) and shows very similar results to those from the K/Pg stratotype section. Diverse and abundant dinocyst assemblages were recovered, and an increase in the abundance of *Cribroperidinium* sp. A of Brinkhuis and Schiøler (1996) in the lowermost Danian is noted.

7.3 Interpretation of results from Stevns Klint

In the present study, only four dinocyst taxa are found to be present throughout the productive samples. These are *A. ramulifera*, *S. ramosus ramosus*, *S. ramosus gracilis* and *T. xanthiopyxides*. These are all cosmopolitan species (Brinkhuis et al., 1998) and are considered characteristic of normal, marine shelf environments (Sluijs et al., 2005).

The K8/7 and K8/5 samples of the coccolith-rich chalk both contain *P. grillator* (112 and 110 specimens, respectively) and *T. xanthiopyxides* (9 and 4 specimens, respectively) and, therefore, confirm previous research on the uppermost Maastrichtian (Wilson, 1974; Hultberg, 1986; Schiøler and Wilson, 1993). The predominance of *P. grillator* and, to a lesser extent, species of *Achomosphaera* (29 and 32 specimens, respectively) and subspecies of *Spiniferites ramosus* (51 and 49

specimens, respectively), is consistent with other findings at Stevns Klint (e.g., J.M. Hansen, 1977; Hultberg, 1986; Brinkhuis et al., 1998). *Palaeoperidinium pyrophorum* is the only peridinioid cyst encountered in the Maastrichtian samples. Its highest abundance (15 specimens) occurs in sample K8/7.

Of the other Kulstirenden samples within the coccolith-rich chalk, KUL/I was barren but KUL/K yielded assemblages very similar to K8/7 and K8/5 samples, with a predominance of *P.grallator*, *I. cristatum* and the associated *Achomosphaera* /*Spiniferites* complex of species. Consequently, the G/P^{species} ratio for the Maastrichtian is also at its highest here (based on one peridinioid species), although it still remains low (K8/7 G/P ratio = 25). Samples with a G/P^{species} ratio of 18 are considered by Harland (1973) as being indicative of a marine environment. Hultberg (1986) is the only other author to have calculated the G/P ratio at Stevns Klint showing values of 1–300, using the number of specimens. Our findings here are consistent with Hultberg (1986) for the Maastrichtian, which also shows gonyaulacacean-dominated assemblages for the upper Maastrichtian. The G/P^{species} ratio calculated here varies between 0 and 29 and G/P^{specimens} ratio varies from 0 to 304, both showing a decreasing trend through the Maastrichtian and into the Danian. Hultberg's (1986) G/P ratio varied between 75 and 300 in the Maastrichtian chalks, decreasing to <50 at the base of the Fiskeler Member. *Palynodinium grallator* and *H. tubiferum tubiferum* are both considered to be indicative of high-latitude climates (Brinkhuis et al., 1998), with the latter "*Hystriosphæridium*-type" being noted for its ability to tolerate stressed environments (Schjøler et al., 1997). Their combined presence and the high abundances of *P. grallator* are, therefore, indicative of relatively cool climatic conditions at this time.

Within the Højerup (L5) samples of the 'Grey Chalk', the *Achomosphaera*–*Spiniferites* complex cysts dominate the flora, replacing *P. grallator* as the major taxon, although *T. xanthiopyxides* becomes increasingly abundant (14–37 specimens) and is one of the most common species in the three uppermost samples. *Spiniferites ramosus ramosus* and *S. ramosus gracilis* are also very common in these samples. While *P. grallator* remains present, its abundance is relatively low compared to the K8 samples. In contrast, *Impagidinium* spp. becomes a major component of the assemblage, their highest abundances occurring in the lowermost samples.

The biostratigraphy shows that *P. grallator* was observed rarely at the base of the Fiskeler Member. This agrees with Brinkhuis et al. (1998) who found this species in the bottom layer of the Fiskeler Member. Moreover, Hultberg (1986) had previously noted *P. grallator*, in parts of Stevns Klint, in Layer 3 (Christensen et al., 1973) of the Fiskeler Member; while in other parts of the peninsula its range was found to extend only to Layer 1. Hultberg drew two main conclusions from these findings: (i) that the Fiskeler Member is Maastrichtian in age, and (ii) had been deposited diachronously over Denmark. This was in marked contrast to other fossil and geochemical evidence, including the large negative shift in the $\delta^{13}\text{C}$ record (e.g., Hart et al., 2005, fig. 10) record from Stevns Klint. The top of the Højerup Member and therefore, the end of the Maastrichtian in higher latitudes can be defined by the last common occurrence of *P. grallator*. Our data clearly support a Danian age for the Fiskeler Member at this location. The 'diachronism' reported by Rasmussen et al. (2005) for the planktic foraminiferal zonation is considered an artefact of the variation in thickness of the Fiskeler Member and the position of the facies change to the Cerithium Limestone Member. The iridium spike that is recorded within K/Pg

boundary sediments from a variety of locations (Alvarez et al., 1980), however, precludes diachronous deposition as does the global correlation of the $\delta^{13}\text{C}$ data (Hart et al., 2005; Hart et al., 2014).

The *D. californicum* Zone is representative of the Danian. In contrast to data presented by Kjellström and Hansen (1981), however, the expanded section of the Fiskeler Member studied here documents only an intermittent presence of *D. californicum* and in reduced numbers. Hultberg (1986) and Brinkhuis et al. (1998) did not record *D. californicum* at Stevns Klint, confirming its rareness. This suggests that, although the *D. californicum* Zone has been applied relatively successfully to the rest of southern Scandinavia, this zonation is difficult to apply at Stevns Klint, or at least a part of it. The rare occurrence of *S. inornata*, a species that is supposed to be coincident with *D. californicum* throughout the lower parts of the Danian, supports this zonation. With the mass extinction of calcareous nannofossils and almost all planktic foraminifera at the K/Pg boundary, there is a dramatic loss of sediment supply leaving only a thin clay-rich succession and an apparent concentration of organic-walled microfossils. Even our small samples, therefore, represent a significant interval of time as indicated by the precessional cyclicity in the $\delta^{13}\text{C}$ data (Hart et al., 2005; Leighton et al., 2017). If this is true in the expanded succession seen at Kulstirenden then it is particularly so in the thinner successions (e.g., at Højerup). If greater condensation of sediments has occurred in these thinner sections, then each sample represents a longer period of time. Consequently, species that were only intermittently present might appear to be present throughout the whole time represented by the sediment. For this location, therefore, it is proposed that the lowermost Danian is defined by the appearance of *Cribroperidinium* sp. A of Brinkhuis and Schiøler (1996) together with the

appearance of *S. inornata* and *D. californicum* because *C. cornuta* s.s. is not present. In the middle of the Fiskeler Member (sample KU23), *X. reticulatum* appears and characterises an *X. reticulatum* Sub-zone. With all dinocyst taxa disappearing in the Cerithium Limestone Member and the overlying Korsnæb Member the vertical extension of this sub-zone is not currently known.

Another feature of the KU (14–50) samples of the Fiskeler Member is the predominance of *T. xanthiopyxides*, where it commonly represents approximately one-third of the assemblage. Previous studies have shown this species to be present in all stratigraphic levels at Stevns Klint, but no one has commented on its predominance within this stratigraphic level. Indeed, both H.J. Hansen et al. (1986) and Brinkhuis et al. (1998) show *T. evittii* to be the dominant species through layers 2 and 3 of the Fiskeler Member. *Trithyrodinium evittii* is also found to be common to very common (19–48 specimens in samples KU18–27) within the Fiskeler Member in our study and becomes abundant in the topmost samples (KU28 and KU29, recording 163–214 specimens, respectively). Another peridinioid, *Manumiella seelandica* (as *M. druggii*) has previously been reported to be abundant in these sediments at the base of the Danian (Hultberg, 1986) but these data are not confirmed here. In the current study occasional specimens of *M. seelandica* are found at the base of the Fiskeler Member, becoming more common (5–14 specimens) in the topmost samples (KU26–KU29). Instead of abundant *M. seelandica*, large numbers of *T. evittii* are recorded here and this confirms the results of Brinkhuis et al. (1998).

The lack of dinocysts, and the presence of bisaccate pollen, which have a hinterland provenance (Schiøler et al., 1997), could be due to variable preservation

and/or complex diagenesis of the Cerithium Limestone Member (Rasmussen et al. 2005).

7.4 Palaeoenvironmental interpretation

The Gonyaulacoid/Peridinioid (G/P) and Protoperidinioid /Gonyaulacoid (P/G) ratios were calculated here based on the data collected; the former after Harland (1973), and the latter follows Versteegh (1994). Note that these methods produce different results to those obtained by Hultberg (1986,1987) for samples from Stevns Klint but the overall decreasing trend in the G/P^{species} and $G/P^{\text{specimens}}$ ratios is similar. The method of calculation for the G/P ratio used in Hultberg (1986, 1987) is not clear but probably involved using the number of specimens.

The G/P ratio, based on specimen percentage, was calculated by Prauss (2009) for the K/Pg boundary at Brazos River, Texas. An overall increase in peridinioid cysts was recorded across the K/Pg boundary. This is interpreted as reflecting an increase in palaeoproductivity through the succession, into the Danian. Brinkhuis et al. (1998) found that their P/G ratios did not correlate with the drop in $\delta^{13}\text{C}$ values across the K/Pg boundary at El Kef and interpreted this as reflecting changes in temperature as well as productivity.

Both G/P^{species} and $G/P^{\text{specimens}}$ ratios calculated here display an overall decreasing trend from the uppermost Maastrichtian into the Danian, while the P/G ratio increases. The interpretation here is of a marine environment with increasing nutrients and productivity.

Small numbers of *Impagidinium cristatum* (10 specimens) occur in the Sigerslev Member (K8/7) with an increased abundance occurring in the stratigraphically younger K8/5 (20 specimens). *I. cristatum* is considered to be

indicative of more oceanic rather than neritic conditions (Schjøler et al., 1997), and so its presence indicates that there was still an open marine influence to the environment in the Danish Basin. This is recognised by Sheldon et al. (2010) as an anti-clockwise circulatory system in the Danish Basin with possible warmer water influences coming from the southeast. The decrease in abundance of *I. cristatum* and other *Impagidinium* spp. implies a shallowing-upward sequence.

Bromley (1979) and Hart et al. (2004, 2005) suggest that the succession of the Højerup Member represented a shallower environment compared to the white coccolith chalk below (Sigerslev Member). The stable isotope data derived from benthic foraminifera (Schmitz et al., 1992; Hart et al., 2005) provide evidence that, although shallower, the environment was still open marine.

This shallowing upwards is confirmed by the occurrence of *Senoniaspharea inornata* in the Fiskeler Member (KU14-29). This species belongs to the *Areoligera* group of Gv cysts (Fensome et al., 2008) which has been interpreted as reflecting high energy, shallower environments (Sluijs et al., 2005). The occurrence of this species at Stevns Klint, reflects the shallower conditions both above, and near to the Rynkøbing-Fyn High in comparison to the more basinal area of northern Jutland (Jylland).

Brinkhuis et al. (1998, p.77) indicate that the differences between their results and those of Hultberg (1986) were the result of the processing techniques employed and then conclude (Brinkhuis et al. 1998, p.80) that there were warm, stable conditions in the latest Maastrichtian, and cooler but fluctuating conditions in the earliest Danian, with water masses controlling the migration and distribution of taxa. In the past, *T. evittii* has been used as a warmer-water, low latitude indicator species and as a peridinioid, it also indicates increased primary productivity (Brinkhuis et al.,

1998, fig.6). The abundance of *T.evittii* in the lower Danian at Stevns Klint agrees with observations made by Brinkhuis et al. (1998) and others (e.g., Aydin, 2013; Pross and Brinkhuis, 2005).

8 Conclusions

The evidence obtained from this investigation of the dinocysts provides data that helps to document the changes across the Maastrichtian/Danian (K/Pg) boundary. Our results do not replicate those of earlier studies, although, this may be due to the limited number of samples analysed in previous investigations, the sample interval, sampling from thinner sections of the Fiskeler Member or the processing techniques adopted (e.g. Hultberg, 1986). Also previous authors have rarely identified their precise sample locations on Stevns Klint, so lateral variations, as indicated by the variable lithology may account for some of these differences.

The top of the Højerup Member and, therefore, the top of the Maastrichtian is characterised by the last common appearance of *P. grallator*. Within the Fiskeler Member, the intermittent presence of *D. californicum* precludes its use as a primary biostratigraphical indicator although, when used together with other biostratigraphically useful species such as *S.inornata*, *X. reticulatum* and *T.evittii*, the lowermost Danian can be characterised. Conditions throughout the latest Maastrichtian and the early Danian, as indicated by the G/P ratio, were changing and becoming dominated by peridinioid dinocysts at the base of the Danian, reflecting an increase in primary productivity (Sluijs et al. 2005).

Although our sampling was at a much higher resolution than earlier investigations and from an expanded succession of Fiskeler Member, there is still the potential for further dinocyst work at Stevns Klint and additional refinement of the

biostratigraphy, especially if coupled with data from successions in North Jutland (Jylland) and off-shore.

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Figures, Table and Plate Captions

Fig. 1. Locality map of Stevns Peninsula, eastern Denmark and its location in Southern Scandinavia.

Fig. 2. Revised lithostratigraphy of the succession exposed on Stevns Peninsula, following Hart et al. (2005) and Surlyk et al. (2006).

Fig. 3. Photograph of the beach section north of Højerup church, showing the horizontal chalk in the lower part of the cliff, the prominent flint line (above which is the incipient hardground) and the Fiskeler Member deposited in troughs picked out by the dune-like structures in the Højerup Member.

Fig. 4. (a) Photograph of the Fiskeler Member at Kulstirenden prior to sampling. The distinctive Fe-stained horizon is just below the scale card, at the base of the Fiskeler Member; (b) the marked thinning of the Fiskeler Member to the north of the sampling location.

Fig. 5. Composite log of the Cretaceous/Palaeogene boundary succession.

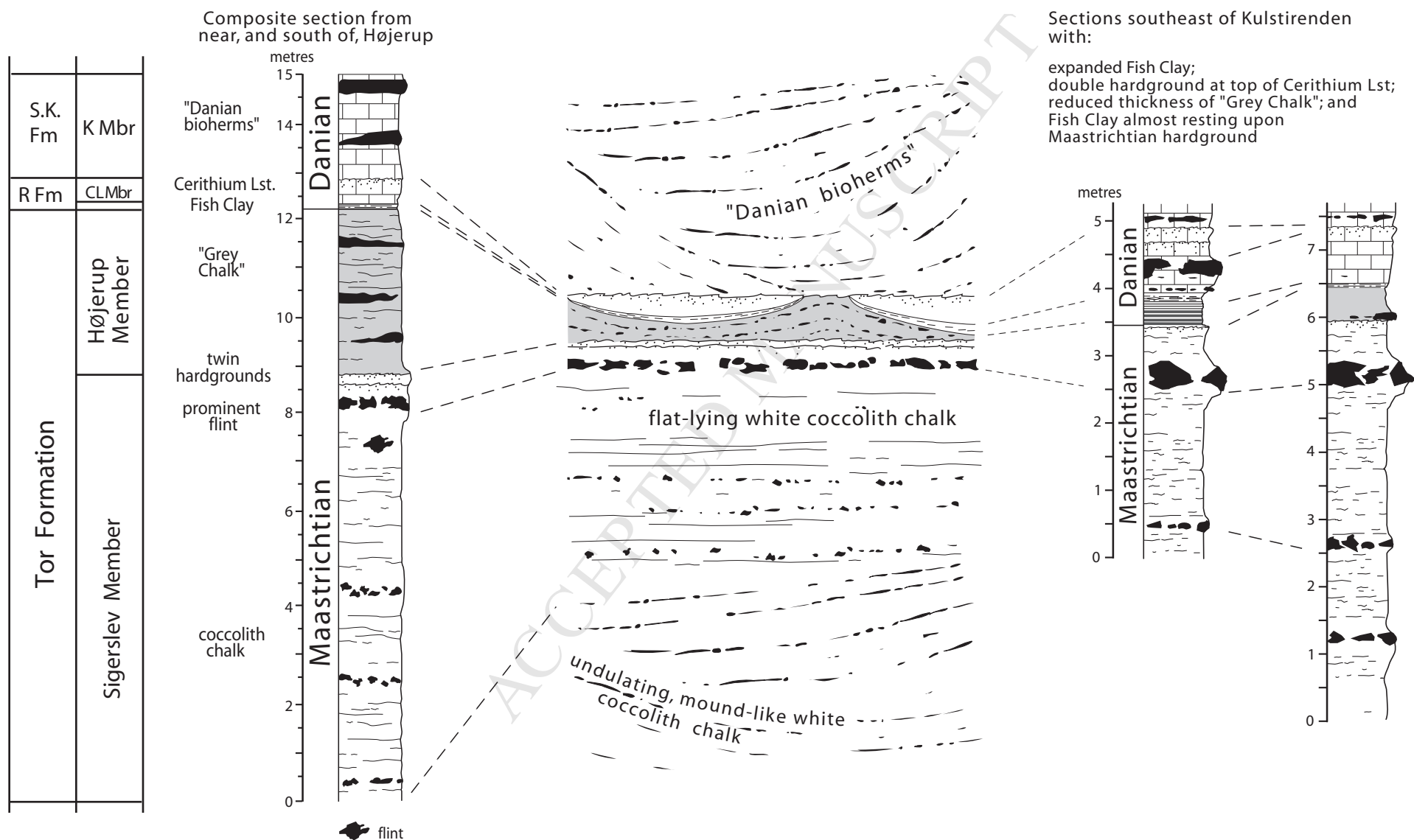
Fig. 6. A) *Palynodinium grillator*; B) *Thalassiphora pelagica*; C) *Palaeoperidinium pyrophorum*; D) *Hystriospheraidium tubiferum*; E) *Spiniferites ramosus reticulatus*; F) *Spiniferites ramosus*; G) *Impagidinium cristatum*; H) *Tanyosphaeridium xanthiopyxides*; I) *Damassadinium californicum*; J) *Cribroperidinium* sp. A of Brinkhuis and Schiøler (1996); K) *Xenicodinium reticulatum*; L) *Manumiella seelandica*; M) *Cerodinium diebelii*; N) *Trithyrodinium evitti*. Scale bar 10µm in all images.

Fig. 7. Gonyaulacacean/Peridiniacean (G/P) ratio calculated using species and specimen numbers. Peridiniacean/Gonyaulacacean (P/G) ratio ((Versteegh, 1994). Total number of species counted in each sample.

Table 1. Occurrences of selected taxa. ○ < 5 specimens; ● >5 specimens. CLM - Cerithium Limestone Member; SM - Sigerslev Member

Appendix 1. Raw data of dinocyst counts. * marks taxa which require further taxonomic investigation.

[illegible]



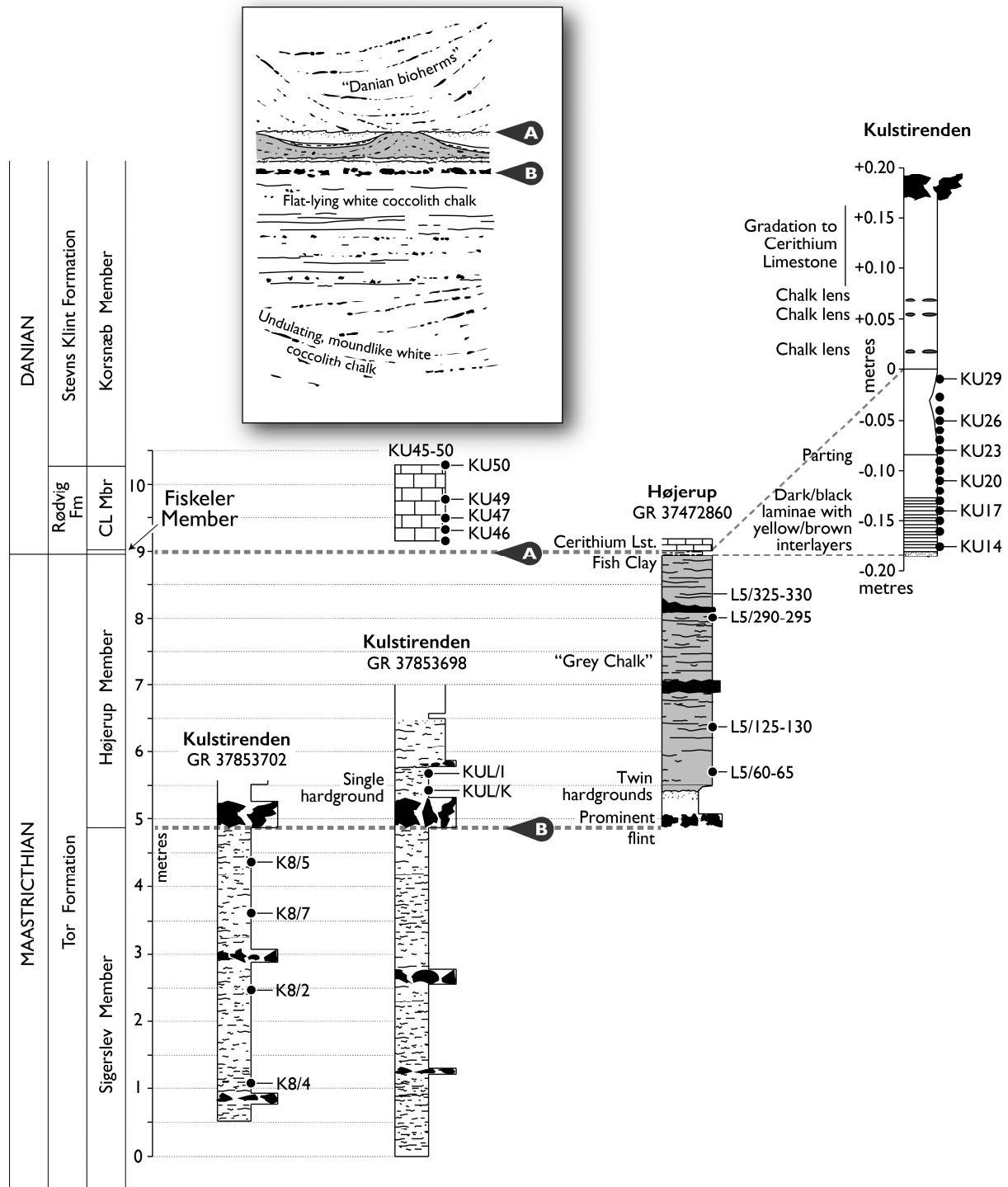
SK Fm. - Stevns Klint Formation
R Fm. - Rødvig Formation

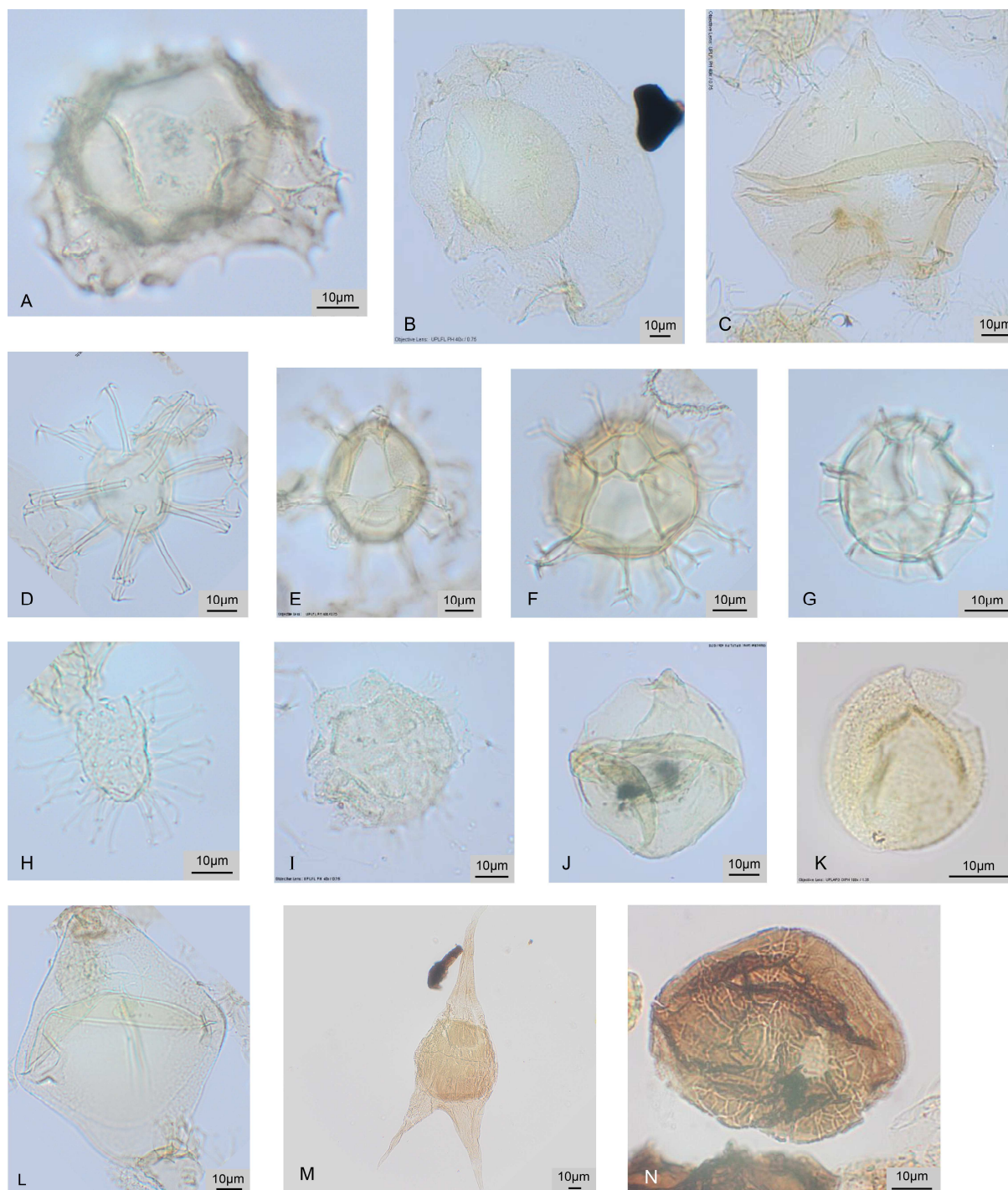
K Mbr. - Korsnæb Member
CL Mbr. - Cerithium Limestone Member

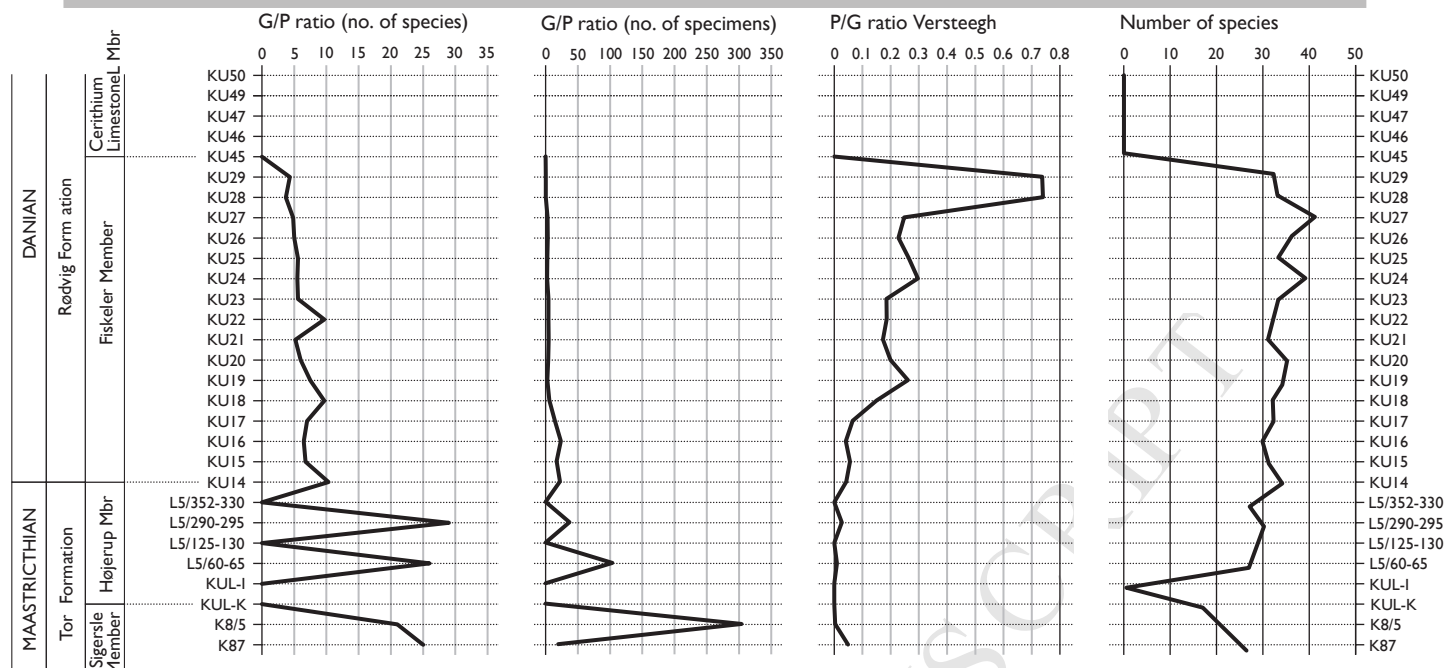












Highlights – Fitzpatrick *et al.*

The Cretaceous-Paleogene boundary succession at Stevns Klint is world famous and been a reference point for stratigraphy since the mid-nineteenth century. It is now a World Heritage Site and one of the most important of the distal K/Pg sites. Previous dinocyst research on the Stevns Klint succession has caused controversy, with some strange assemblages being described that may have been the result of preparation techniques. Unfortunately most of the sampling across the boundary has been limited to only a few sample points, often where the boundary clay (Fiskeler Member) is at its thinnest. Our research, using a large number of samples from an expanded succession of the boundary clay, has resolved many of the earlier problems and allowed us to identify a dinocyst stratigraphy across the boundary. This dinocyst stratigraphy can be used to compare the Stevns Klint succession with other boundary sections in Tunisia and Texas. One of the earlier suggestions, that the boundary clay is diachronous (despite containing the iridium anomaly), has been refuted.